Imaging Techniques in Spinal Cord Injury

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Key words
- Cord
- Imaging
- Injury
- Spinal

Abbreviations and Acronyms
ADC: Apparent diffusion coefficient
CT: Computed tomography
DCE: Dynamic contrast-enhanced
DTI: Diffusion tensor imaging
FA: Fractional anisotropy
fMRI: Functional MRI
MRI: Magnetic resonance imaging
PET: Positron emission tomography
SCI: Spinal cord injury

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Citation: World Neurosurg. (2013). http://dx.doi.org/10.1016/j.wneu.2012.12.004

Journal homepage: www.WORLDNEUROSURGERY.org

Available online: www.sciencedirect.com

1878-8750/$ - see front matter

BACKGROUND: **Spinal imaging plays a critical role in the diagnosis, treatment, and rehabilitation of patients with spinal cord injury (SCI). In recent years there has been increasing interest in the development of advanced imaging techniques to provide pertinent microstructural and metabolic information that is not provided by conventional modalities.**

METHODS: **This review details the pathophysiological structural changes that accompany SCI, as well as their imaging correlates. The potential clinical applications of novel spinal cord imaging techniques to SCI are presented.**

RESULTS: **There are a variety of novel advanced imaging techniques that are principally focused on the microstructural and/or biochemical function of the spinal cord, and can potentially be applied to traumatic SCI, including diffusion tensor imaging, magnetic resonance spectroscopy, positron emission tomography, single-photon emission computed tomography, and functional magnetic resonance imaging. These techniques are presently in various stages of development, including some whose applications are primarily limited to laboratory investigation, whereas others are being actively used in clinical practice.**

CONCLUSION: **Advanced imaging of the spinal cord has tremendous potential to provide patient-specific physiological information about the status of cord integrity and health. Advanced spinal cord imaging is still at early stages of development and clinical implementation but is likely to play an increasingly important role in the management of spinal cord health in the foreseeable future.**

INTRODUCTION

Spinal imaging plays an essential role in the diagnosis, treatment, and rehabilitation of patients with spinal cord injury (SCI). Traditionally, these modalities have consisted of plain radiography (Figure 1A), computed tomography (CT; Figure 1B), and magnetic resonance imaging (MRI; Figure 1C and D). In combination, these techniques provide excellent macrostructural information regarding the classification and magnitude of the osseous and ligamentous injury, which, coupled with the clinical examination, guides patient management.

Despite their critical importance, these modalities offer comparatively less information regarding the microstructural injury to the spinal cord, and correlations between the radiographic and clinical findings largely have been limited. In part this has lead to the development of novel imaging techniques that are principally focused on the microstructural and/or biochemical function of the spinal cord, including diffusion tensor imaging (DTI), magnetic resonance spectroscopy, positron emission tomography (PET), single-photon emission computed tomography, and functional MRI (fMRI). These techniques are presently in various stages of development, including some whose applications are primarily limited to laboratory investigation, whereas other are being actively used in clinical practice. This review outlines the major structural and vascular changes that are expected to accompany the phases of traumatic injury of the spinal cord, along with the imaging correlates of these physiological changes. The application of conventional and novel imaging techniques to SCI will be discussed.

PHASES OF SCI

Hyper-Acute and Acute Spinal Trauma

The hyper-acute and acute stages of SCI, typically referring from the time of traumatic insult to hours after the initial injury, result in direct mechanical injury as well as other indirect effects including local hypoxia, ischemia, hemorrhage, and edema. Mechanical disruption of neural tissue structure results in immediate death of cells in the region of the insult. The stretching and tearing of large axons results in damage to axonal membranes and an increase in membrane permeability (82). Magnetic resonance spectroscopy clearly demonstrates a decrease in N-acetyl aspartate, a neuronal marker, after traumatic SCI in animal models (69). When diffusion MRI, which is sensitive to the magnitude of water self-diffusion, is used, early axonal

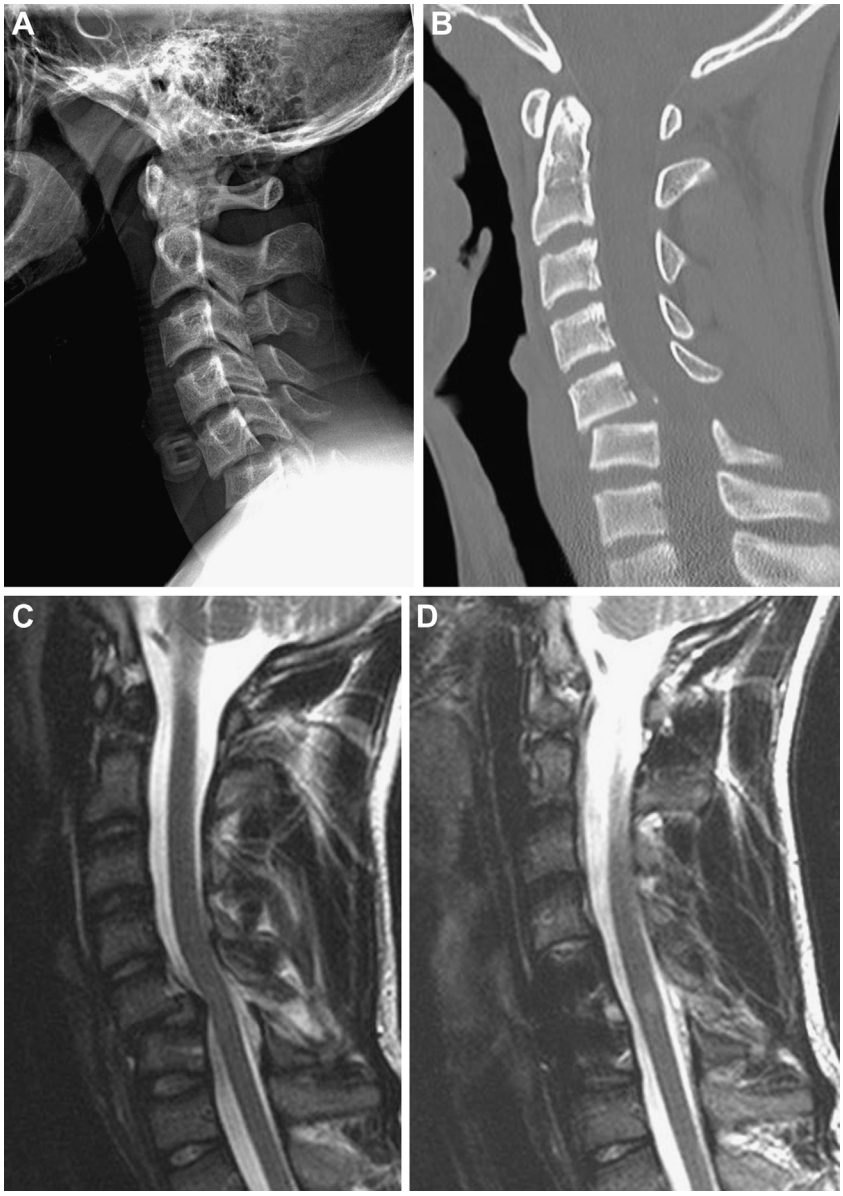

Figure 1. A 17-year-old man who noted paresthesias and upper-extremity weakness after falling. Plain radiography (**A**) and CT (**B**) demonstrate a traumatic C5-6 subluxation with jumped facets. (**C**) MRI showed a traumatic disk herniation, which prompted an anterior surgical approach. (**D**) MRI at 1 year postoperatively demonstrates alleviation of the spinal canal stenosis, yet focal spinal cord hyperintensity remains.

death and the disruption of the cell membranes has been shown to result in elevated apparent diffusion coefficient (ADC) in animal studies (22, 38), numerical simulations (37, 40), and human patients (16, 32, 74, 95). Despite these intriguing observations, hyperacute imaging of SCI is relatively difficult in the clinical scenario because patients often are admitted after this stage of injury.

Some of the earliest imaging changes after SCI are the result of hemorrhages in the central gray matter adjacent to the central canal that spread radially from the central canal into the anterior horns and neighboring white matter regions around the injury epicenter and extend both rostrally and caudally (45, 75, 89). CT is ideally suited for identifying acute hemorrhage after SCI (23, 87) because it shows hyperdense regions in areas of blood products. MRI techniques that are sensitive to changes in magnetic susceptibility, or susceptibility-weighted images, are also useful for identifying hemorrhagic lesions because of the sensitivity to microscopic magnetic perturbations from iron products after spinal trauma (92). Blood products may also be visible as hyper-intensity on precontrast T1-weighted images (36, 59) because the iron within the blood can dramatically shorten tissue relaxation rates.

Compressive or impact-induced spinal trauma often causes restriction of blood flow to the injury site (24, 49, 72). Arterial spin labeling, an MRI technique that uses magnetization tagged blood water in an artery and to quantify blood flow, has been successfully used to quantify blood flow in the mouse spinal cord (16, 25), although similar results in humans have not yet been obtained. Dynamic contrast-enhanced (DCE) MRI, an MR technique that uses a pharmacokinetic model for contrast agent extravasation from the vascular to the extravascular space to quantify blood volume and vascular permeability, also has been used to successfully quantify vascular changes in animal models (7-9, 17), but again analogous studies in human SCI have not yet been performed.

Similarly, the DCE approach has been successfully applied to CT-contrast agents in the spinal cord after injury and demonstrated a decrease in blood flow and volume after acute spinal trauma in animals (44, 54). DCE applied to CT has only recently been shown to be feasible in humans (10); thus, this technique may be useful in the very near future when applied to either CT or MRI data. Other techniques for imaging blood flow can be performed in the spinal cord, including PET imaging using radiolabeled water (H_2-[^{15}O]), single-photon emission computed tomography imaging, xenon-enhanced CT, and phase-contrast MRI; however, these techniques are not yet routinely performed after spinal trauma.

The reduction in blood flow commonly observed often results in a decrease in oxygen tension (24, 48, 83), forcing neural tissue to use anaerobic metabolic pathways in the form of high-energy phosphates, resulting in an overall decrease in metabolism for up to four hours after